Thin-Film Photovoltaic Solar Array Parametric Assessment

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ABSTRACT
This paper summarizes a study that had the objective to develop a model and parametrically determine the circumstances for which lightweight thin-film photovoltaic solar arrays would be more beneficial, in terms of mass and cost, than arrays using high-efficiency crystalline solar cells. Previous studies considering arrays with near-term thin-film technology for Earth orbiting applications are briefly reviewed. The present study uses a parametric approach that evaluated the performance of lightweight thin-film arrays with cell efficiencies ranging from 5% to 20%. The model developed for this study is described in some detail. Similar mass and cost trends for each array option were found across eight missions of various power levels in locations ranging from Venus to Jupiter.

The results for one specific mission, a main belt asteroid tour, indicate that only moderate thin-film cell efficiency (~12%) is necessary to match the mass of arrays using crystalline cells with much greater efficiency (35% multi-junction GaAs based and 20% thin-silicon). Regarding cost, a 12% efficient thin-film array is projected to cost about half as much as a 4-junction GaAs array. While efficiency improvements beyond 12% did not significantly further improve the mass and cost benefits for thin-film arrays, higher efficiency will be needed to mitigate the spacecraft-level impacts associated with large deployed array areas. A low-temperature approach to depositing thin-film cells on lightweight, flexible plastic substrates is

briefly described. The paper concludes with the observation that with the characteristics assumed for this study, ultra-lightweight arrays using efficient, thin-film cells on flexible substrates may become a leading alternative for a wide variety of space missions.

INTRODUCTION
Very lightweight and low cost photovoltaic (PV) solar arrays based on thin-film PV array technology have held much promise for future space missions. While sample thin-film cells and panels have flown in space (LIPS-III in 1987, PASP-Plus in 1994, the Mir space station in 1998) and are planned to fly (Earth Observing-1 in 2000), a complete solar array consisting of thin-film cells has yet to be built. Also, the projected array-level efficiency of thin-film PV is currently much less than that of arrays based on advanced thin-crystal silicon (Si) and multi-junction gallium arsenide (GaAs) based cells. Consequently, at the spacecraft level, the large deployed array area required for thin-film arrays offsets or even negates its lower array mass and cost benefits. Until thin-film PV efficiency improves and manufacturing methods to deposit the thin-films on lightweight substrates over large areas are refined, future space missions will most likely keep using high efficiency silicon or multi-junction PV planar and/or concentrator arrays. As thin-film PV technology for use in space improves, more applications will consider its advantages, namely low cost, low mass, improved radiation tolerance[1], and high specific power (W/kg).

Figure 1 depicts two ways to obtain very high specific power using photovoltaic arrays. Flexible planar arrays of moderate area density (1-2 kg/m^2) using either relatively heavy but very efficient multi-junction solar cells, or relatively lighter but less efficient thin silicon cells, could obtain an array-level specific power approaching 300 W/kg. To get to this level, new solar

array substrates, support structures and deployment concepts may be needed in conjunction with improved cell technology.[2] Ultra-lightweight arrays (0.25 to 0.75 kg/m^2) using lightweight thin-film solar cells of moderate efficiency may enable the attainment of even greater array-level specific power. As the plot in figure 1 implies, ultra-lightweight thin-film arrays may be the most feasible means of approaching the very high specific power necessary to enable missions with very high power requirements, such as space solar power satellites, manned Mars or lunar missions and some solar electric propulsion concepts.[3, 4]

The objective of the present assessment is to develop a model and parametrically determine the circumstances, both in terms of solar array technology and mission scenarios, for which thin-film PV solar arrays would be more beneficial than alternatives. NASA Glenn research Center's (GRC) approach to depositing thin-film cells on lightweight substrates with the aim of ultimately achieving higher efficiencies is also described.

BACKGROUND
A number of past studies have compared solar cell and array technologies for Earth orbiting missions. Ralph performed system trades for presently available and near-term crystalline and thin-film cells on rigid, flexible and concentrator arrays in Low Earth Orbit (LEO) and Geostationary Earth Orbit (GEO).[5, 6] Ralph's results in reference 5 indicate that GEO arrays using high efficiency multi-junction GaAs cells have mass and cost advantages over alternatives, especially when the area penalty (increased attitude control fuel) of arrays using the less efficient thin-film cells is included. With Ralph's assumptions, thin-film cell efficiency needs to be at least 12.6% to be competitive in GEO. For LEO, Ralph concluded that while the most efficient multi-junction cell array has the lowest mass, arrays with 9% to 12.6% efficient thin-film cells have competitive area-adjusted costs.

In a similar study, Gaddy looked at the cost performance of multi-junction GaAs and advanced Si arrays on small, medium and large LEO spacecraft.[7] This study included the cost of the spacecraft support to the payload and concludes that the most efficient multi-junction arrays result in the greatest spacecraft-level mass and cost benefits.

The paper by Bell outlines a model developed by the Aerospace Corporation to "determine optimal power subsystem suites as a function of spacecraft design and total system cost."[8] Example model results are reported for a 100 satellite high-power (15kW) LEO constellation and a small, single-mission 1 kW LEO

satellite. Study results for both cases favored high efficiency cell solar arrays. Because satellites in the LEO constellation were delivered to a low parking orbit and then transferred to the final 1852 km orbit, the large area of the 8% to 10% efficient thin-film arrays led to significant attitude control system impacts, and ultimately higher mission costs. For the single-mission low power LEO case, the Aerospace model favored mature, low nonrecurring cost array technologies using 16% efficient Si and 21.5% efficient GaAs cells.

Each of the studies reviewed above looked at near-term thin-film cell technology on flexible, but not necessarily lightweight arrays for Earth orbiting applications. Only when the cell efficiency of a thin-film array was greater than 10% did they compare favorably with crystalline cell arrays for some of the missions studied. In the present study, the performance of ultra-lightweight thin-film arrays with assumed cell efficiencies ranging from 5% to 20% are evaluated for missions in Earth orbit and beyond.

ANALYTICAL APPROACH
One objective of this study is to estimate the improvement in cell efficiency required for thin-film arrays to be more competitive with higher-efficiency crystalline cells from a mass and area perspective. From a mass perspective, array specific mass is the figure of merit. Array specific mass can be obtained by dividing the specific area (W/m^2) by the array's area density (kg/m^2). Specific area is a function of the cell efficiency and array packing factor. Area density is a function of the cell material density and thickness and the array substrate, wiring, support structure and mechanisms. To a first order, the cell efficiency required to match the specific power of an array of a given type but using different cells (i.e. the array area density not including cells is assumed to be constant) can be estimated with the following equation,

$$\eta_{TF} = \eta_2 \left(\frac{PF_2}{PF_{TF}} \right) \left(\frac{Array + Cell_{TF}}{Array + Cell_2} \right) \tag{1}$$

where η is the cell efficiency, PF is the array packing factor, $Array$ is the area density (kg/m^2) of the array, including its wiring, substrate, support structure and mechanisms, and $Cell$ is the cell area density. While the array area density is held constant in this first order approximation, in actuality, it should decrease with the use of lighter cell technology. The more detailed array model discussed later accounts for this effect.

Figure 2 shows the approximate thin-film cell efficiency required to match the specific power of a high efficiency cell array using equation 1. Cell

material densities, including the coverglass, of 0.50 kg/m² for the Si cell, 1.0 kg/m² for the multi-junction GaAs cells, and 0.16 kg/m² for the thin-film cells are assumed in figure 2. In practice, the actual cell efficiency required to match array specific mass will also depend on the cell operating temperature and degradation of the cell efficiency from environmental effects over the mission life. Nevertheless, figure 2 can be used to discern trends. For example, the figure shows that for ultra-light arrays (area densities from 0.25 to 0.75 kg/m²), only moderate thin-film cell efficiencies are required to match the specific power of arrays using much higher efficiency, but heavier cells. Improvements in thin-film cell efficiencies may still be necessary in order to reduce the size of thin-film arrays in order to minimize attitude control system impacts and to reduce array stowed volume and deployment complexity for missions with these concerns.

To perform the main analysis of this study, a spreadsheet model was developed that calculates the size and estimates the cost of PV arrays based on different cell and array technologies for a given set of mission requirements. Comparative metrics (e.g. W/kg, W/m², kg/m², etc.) are calculated for various array components, at the array level itself, and then at the power subsystem and spacecraft level.

Representative mission information was gathered for eight missions at various locations in the solar system with various end-of-life (EOL) power requirements. The model was applied to each mission in a parametric fashion in an effort to determine meaningful trends.

MODEL DESCRIPTION

The Array Design Assessment Model (ADAM) was developed to support evaluation of array design alternatives. ADAM includes several integrated array design modules, five databases to manage input set alternatives for running the design modules, and a user interface with input forms and model outputs. Outputs include nearly 100 items representing array performance, including PV array, other power subsystem elements, and spacecraft development. ADAM elements and estimating methodology flow are shown in figure 3.

Mission candidates in the ADAM database cover array sizes from several hundred watts to around 20 kilowatts. Size and costing relationships have not been tested for very small (<100 W) or very large (>25 kW) arrays.

PV Array Sizing

For PV array sizing, ADAM separates the array into several elements, as shown in figure 4. The model first estimates cell area requirements based on cell performance characteristics in the selected operating environment, including the effects of operating temperature, cell mismatch, interconnects, radiation, thermal cycling, contamination deposition, meteoroid and orbital debris, ultraviolet degradation, shadowing, offpointing and the array packing factor. Additional blanket layers are built up based on material selections and layer thicknesses. Many advanced features are incorporated to address scaling issues. For example, as required rigid array wing areas grow, less dense and thicker substrate core materials are used to maintain reasonable structural characteristics.

After all blanket requirements are estimated, structure and mechanical elements are added based on blanket properties and required structural characteristics. ADAM handles structural design differently for rigid and flexible arrays. For rigid arrays, a yoke is used to reduce losses from shadowing and stiffness is based on properties of the blanket panels and hinges between panels. For flexible arrays, a deployable boom is sized to support the panel and meet first fundamental frequency requirements.

For rigid panels, the model uses a sandwich structure, which includes a honeycomb core and aluminum or composite face sheets. A parametric curve, correlating mass to the substrate area has been developed based on past data, and the mass is initially estimated using this curve. The masses of other mechanical elements are computed as a fraction of the substrate mass.

The deployed fundamental frequency is one of the basic requirements of the array, and it is calculated to further validate the sizing and configuration. The natural frequency is calculated using the Jones' equation,

$$f_n = \frac{1.2769}{2\pi} \sqrt{\frac{g}{\delta_{max}}} \qquad (2)$$

where, f_n is the natural frequency in first bending mode, g is the acceleration due to gravity, and δ_{max} is the maximum deflection of array. This is a close approximation of the fundamental frequency of a uniform thin plate of arbitrary shape, having any combination of fixed, partially fixed or simply supported boundaries.

Substrate materials are selected and each layer's thickness is calculated to match the substrate mass estimated earlier. For the purpose of this calculation, the solar array is assumed to be a uniform thin plate and the total deflection under 1 g due to the bending of the substrates and the compliance of the hinge lines is calculated. Hinge stiffness is assumed to be 10^5-10^6 Nm/rad. Details like the aspect ratio of the array are chosen to achieve a fundamental frequency of about 0.5 Hz as the model default, although the user can specify other fundamental frequency values.

In the case of the flexible panel, the total mass of the blanket, cells and all other add-ons is estimated by ADAM's Blanket Design Module. Given the total mass and the aspect ratio of the array, the uniformly distributed mass on the boom is calculated. The boom used in this study is a coilable lattice boom. The diameter of the boom, which is limited to a minimum of 10cm, is chosen to provide the equivalent stiffness, necessary to achieve a user-defined fundamental frequency (typically 0.5 Hz) for the given load.[9] This approach results in boom dimensions and masses that are realistic, even though the strength of the boom in bending or buckling is not taken into account. The mass of the canister is assumed to be 1.5 times the mass of the boom. The mass of the array stowage and tensioning systems is calculated as 25% of the sum of the boom, canister, blanket and wiring masses.

For both rigid and flexible arrays, the mass of a single axis drive actuator (SADA) is accounted for and is assumed to scale linearly with the beginning-of-life (BOL) power level (1.5 kg/kW). Wiring mass for either type of array is assumed to be 1.2 kg/kW.

Array sizing accounts for energy storage to support eclipse operations or other mission requirements. ADAM includes nine PMAD and energy storage inputs to estimate other power subsystem element requirements and additional array output required for charging the storage system.

Cost Assumptions/Methodology
ADAM includes parametrics to estimate spacecraft hardware development costs in fixed year dollars (fiscal year 2000). This covers activities typically performed in Phases B/C/D. Cost estimating relationships (CERs) were developed for each ADAM Reference Mission Candidate using proven methods. For Earth orbiting missions, CERs were derived from the NASA GSFC Space Systems Quick Estimating Guide (Version 2.0, August 1997). For the other planetary missions, SAIC's Planetary Development Model was used. Heritage credits were applied to approximately 75% of each

subsystem and the other 25% is assumed to be new development with available technology. Advanced technology development costs are not included. Parametrics are based on costs per kg for all spacecraft subsystems except power, and are only intended to be accurate for concepts reasonably similar to the selected Reference Mission Candidate. Spacecraft system-level assembly/integration/test costs are estimated to be 15% of the subsystem total. Cost results should be interpreted as relatively representative, not absolute values.

Power system costs are built up from several elements. Hardware costs are estimated at the component-level (e.g. cells, substrate, structures, etc.). Non-recurring costs are assumed to be 50% of the hardware costs, and assembly/integration/test labor is added at a rate of $500 per Watt. Because ADAM does not estimate advanced technology development, each array design concept is assumed to be at an equivalent technology readiness level. Savings from advanced array concepts need to offset costs to demonstrate flight readiness.

Model Inputs/Outputs
Table 1 shows a summary of ADAM's databases, inputs, and outputs. ADAM generates almost 100 output items from over 50 inputs to compare performance of different array design concepts. Four high-level inputs – Mission Type, Operating Environment, End-of-Life (EOL) Power Required, and Array Design Lifetime – interface with the ADAM databases to determine initial default values for 24 Level 1 and 30 Level 2 inputs. Level 1 inputs interface with the model databases to determine Level 2 input defaults. ADAM users can choose to operate at the high-level or modify any Level 1 or 2 input to better represent their array/mission design concept. As the ADAM databases are expanded, model capabilities are enhanced. Future versions of ADAM may incorporate more database candidates and additional/enhanced databases, inputs/outputs, and design modules.

More details describing ADAM can be found in the final review presentation for the task order contract under which the model development was performed.[10]

ANALYSIS CASES
As previously mentioned, this study assessed eight representative missions throughout the solar system: a Venus orbiter, LEO and GEO missions, a lunar lander, a Mars communication orbiter and a Mars lander, a Main Belt Asteroid Tour, and a Jupiter orbiter. Given the lightweight substrate and parametric thin-film cell efficiency assumptions used in this study, the same overall trends were found for all missions.

The results for the Main Belt Asteroid Tour (MBAT) are used to illustrate the trends from the parametric analysis. The MBAT mission was chosen because it is a relatively high power mission using solar electric propulsion (SEP). MBAT mission characteristics are as follows:

- Location — 1.5 AU
- Design Life — 6 years
- EOL Power Required — 7.5 kW (1.5 AU)
- Spacecraft Dry Mass — 560 kg
- Spacecraft Wet Mass — 956 kg

The specific thin-film technology considered in the trade study is a 0.2-mil (5 micron) copper indium disulfide ($CuInS_2$, CIS_2 or CIS2) cell on 0.08-mil of molybdenum and 2 mils of a polyimide, resulting in an area density of 0.16 kg/m^2. The CIS2 cell also contains ZnO and CdS layers and is estimated to cost \$60/W. The BOL, 28 degree C, AM0 cell efficiency for CIS2 is parametrically varied from a low of 6% up to 20%. CIS2 performance metrics are compared with a presumed 35% efficient four-junction (4-j) cell based on single-crystal GaAs/Ge technology (1.1 kg/m^2 and \$400/W) and a 20% efficient single-crystal thin-Si cell (0.55 kg/m^2 and \$220/W). For reference, present state-of-the-art AM0, 1-sun efficiency is about 25% for multijunction GaAs based cells and 17% for thin Si. Both crystalline cells have a 4-mil coverglass. All cells are mounted on a 5-mil composite flexible substrate with a coilable deployment boom sized for a 0.5 Hz minimum first fundamental frequency.

RESULTS
Figures 5 through 8 show the model results in graphical form. Figure 5 plots the PV blanket and total array specific power for each array. Figure 6 depicts the total array area for each array on a relative basis, normalized to the 4-j GaAs case (50 m^2 total). Figures 7 and 8 show the array mass and cost breakdowns on a relative basis, again normalized to the 4-j GaAs case (121 kg, \$14.1M total array mass and cost).

DISCUSSION
Pertaining to specific power, figure 5 shows the arrays with 4-j GaAs and Si crystalline cells have comparable values for this key metric at both the PV blanket and total array levels. For the thin-film array, progressively higher specific power at the PV *blanket level* results as a linear function of cell efficiency. However, at the *total array level*, which includes array wiring, structures, mechanisms and a single-axis drive actuator for pointing, the increase is not linear and is much less rapid than at the blanket level. This illustrates the

difficulty in attaining very high total-array-level specific power when accounting for all typical array "ancillaries".

With respect to array total deployed area, figure 6 confirms what is expected – area scales linearly with cell efficiency (assuming similar packing factors and mission cell efficiency knockdown factors). For the MBAT mission, unbalanced drag torques would not be a problem for the much larger array sizes with the lowest thin-film cell efficiencies. However, other disturbance torques and or spacecraft/array slewing to maintain SEP thrust vectors may be an issue.

Figure 7 indicates that for the assumptions underlying the present study, a moderate thin-film cell efficiency of 12% is necessary to match the total mass of arrays using crystalline cells with much greater efficiency. The array component mass breakdowns reveal the leading contributors to each array's total mass. Mechanical components, which include the array stowage and tension mechanisms and SADA contribute a significant portion to all arrays. The cell and coverglass mass dominate the crystalline PV blanket mass, while the substrate mass dominates the thin-film blanket. This highlights the point that in order to take full advantage of the mass benefits of thin-film cell technology, very lightweight substrates and support structures are necessary.

The cost breakpoint for the thin-film arrays occurs at thin-film efficiencies greater than 12% according to figure 8, resulting in an array that costs about half as much as the 4-j GaAs array. Improving the thin-film cell efficiency beyond 12% did not significantly further improve the cost benefit.

THIN-FILM CELL DEVELOPMENT AT GRC
Among the desirable attributes in any space-bound component, subsystem or system are high specific power, radiation tolerance and high reliability, without sacrificing performance. NASA GRC is currently developing space-bound technologies in thin film chalcopyrite solar cells and thin-film lithium polymer batteries. The thin-film solar cell efforts at GRC are summarized below.

The key to achieving high specific power solar arrays is the development of a high-efficiency, thin-film solar cell that can be fabricated directly on a flexible, lightweight, space-qualified durable substrate. Such substrates include Kapton[TM] (DuPont) or other polyimides or suitable polymer films. While the results of the present study indicate that lightweight thin-film

cells with moderate efficiency on lightweight substrates can compete on a mass basis, higher cell efficiencies will be required to mitigate impacts associated with large array area. Current thin-film cell fabrication approaches are limited by either (1) the ultimate efficiency that can be achieved with the device material and structure, or (2) the requirement for high-temperature deposition processes that are incompatible with all presently known flexible polymides, or other polymer substrate materials.

At GRC, a chemically based approach is enabling the development of a process that will produce high-efficiency cells at temperatures below 300 °C. Such low temperatures minimize the problems associated with the difference between the coefficients of thermal expansion of the substrate and thin-film solar cell and/or decomposition of the substrate.

Polymer substrates can be used in low temperatures processes. As such, thin-film solar cell materials can be deposited onto molybdenum-coated Kapton, or other suitable substrates, via a chemical spray process using advanced single-source precursors, or by direct electrochemical deposition. A single-source precursor containing all the required chemically-coordinated atoms such as copper, indium, sulfur and others, will enable the use of low deposition temperatures that are compatible with the substrate of choice.[11]

A combination of low-temperature electrochemical deposition and chemical bath deposition has been used to produce ZnO/CdS/CuInSe2 thin-film photovoltaic solar cells on lightweight flexible plastic substrates, depicted in figure 9.[12]

CONCLUSION

Once available and space qualified, moderate to relatively high efficiency thin-film cells on lightweight flexible substrates will offer significant mass and cost benefits. This approach may even enable ultra-lightweight solar arrays to attain the very high specific mass required for future high-power missions and applications. Further, as thin-film cell efficiency improves, the packaging, deployment and attitude/control impacts of the larger array area will diminish. With these characteristics, ultra-lightweight arrays using efficient, thin-film cells on flexible substrates may become a leading alternative for a wide variety of space missions.

REFERENCES

1. Woodyard, J., Landis, G., "Radiation Resistance of Thin Film Solar Cells", *Solar Cells*, Vol. 31, No. 4, pp. 297–329, 1991 (also NASA Technical Memorandum TM–103715).

2. Jones, P.A., White, Stephen F., Harvey, T.J., "A High Specific Power Solar Array for Low to Mid-Power Spacecraft", Proceedings of the Space Photovoltaic Research and Technology Conference (SPRAT XII), 1992, NASA CP–3210, pp. 177–187.

3. Landis, G., Hepp, A., "Applications of Thin-Film PV for Space", Proceedings of the 26th Intersociety Energy Conversion Engineering Conference, Vol. 2, pp. 256–261, Aug. 1991.

4. Kerslake, Thomas W., Gefert, Leon P., "Solar Power System Analyses for Electric Propulsion Missions", NASA/TM–1999–209289, SAE 99–01–2449, 34th IECEC, August 1999.

5. Ralph, E.L., Woike, T.W., "Solar Cell Array System Trades – Present and Future", AIAA, 1999.

6. Ralph, E.L., "High Efficiency Solar Cell Arrays System Trade-Offs", IEEE, 1994.

7. Gaddy, Edward M., "Cost Performance of Multi-Junction, Gallium Arsenide, and Silicon Solar Cells on Spacecraft, 25th PVSC, May 1996.

8. Bell, Kevin D., Marvin, Dean C., "Power Generation and Storage Technology Selection for an Optimal Spacecraft System Design", IECEC 1999–01–2531.

9. Conley, Peter, "Space Vehicle Mechanisms: Elements of Successful Design", John Wiley and Sons Inc., 1998.

10. "Thin-Film PV Solar Array Assessment for Satellites, Final Review Report," contract number NAS3–26565, Task Order 31.

11. Hollingsworth, J.A., Hepp, A.F., and Buhro, W.E., *Chemical Vapor Deposition*, Vol.3, pp. 105–108, 1999.

12. Raffaelle, R.P., et al, *Solar Energy Materials and Solar Cells*, Vol. 57, pp.167–178, 1999.
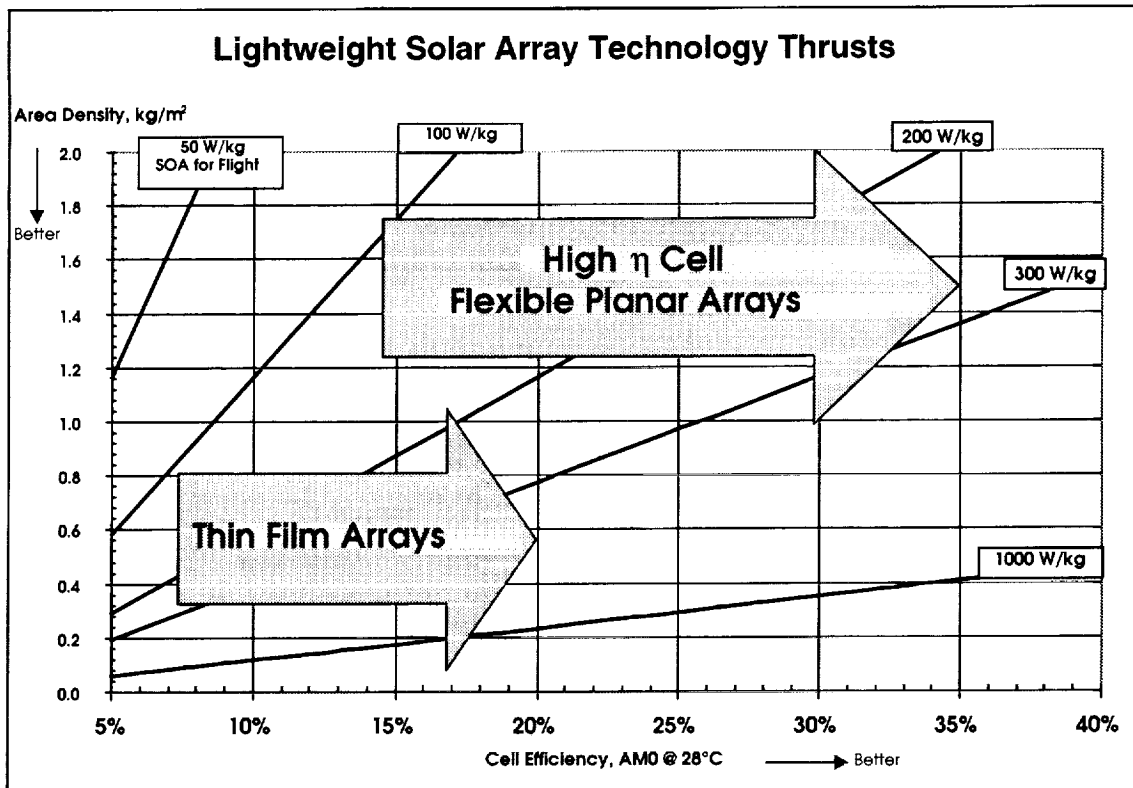
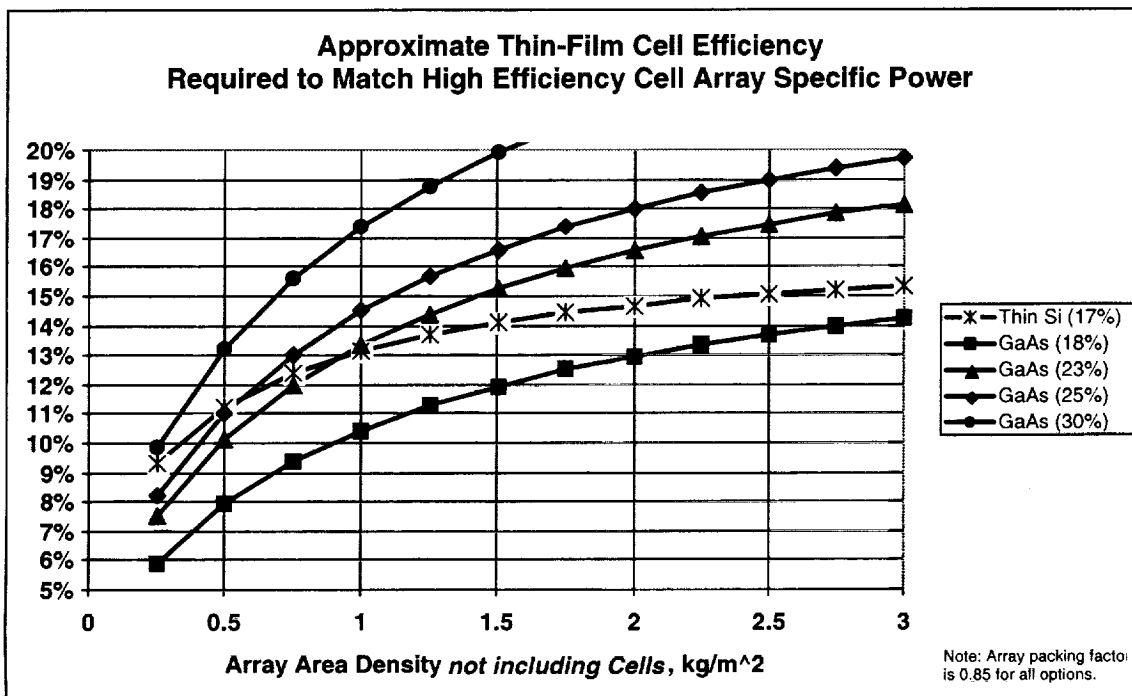**Figure 1 - Lightweight solar array technology thrusts.**

Figure 2 - Approximate thin-film cell efficiency required to match high efficiency cell array specific power.
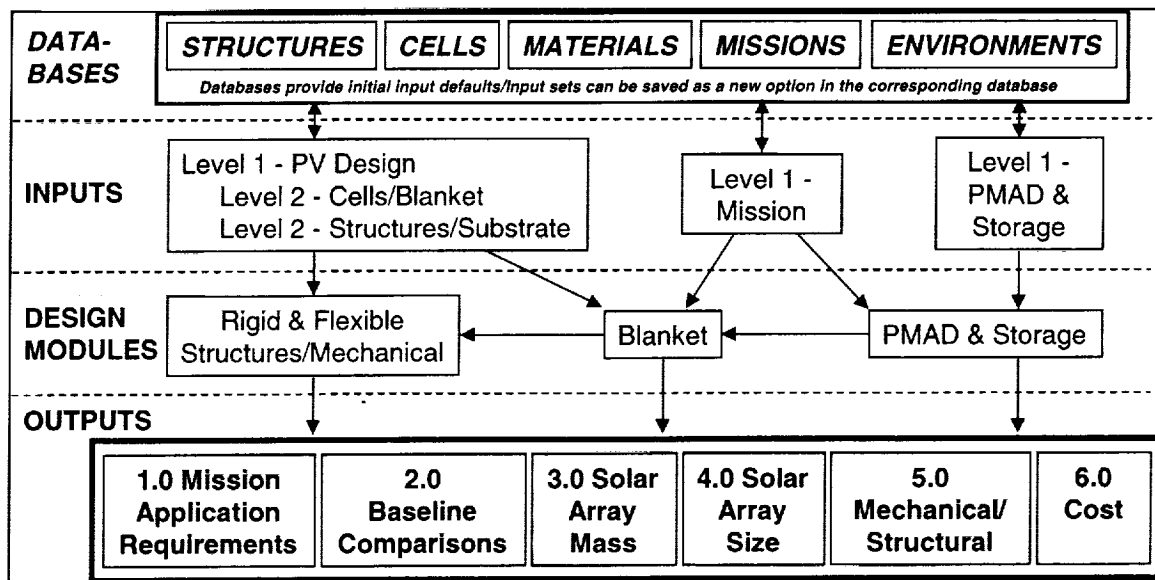
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Figure 3 - ADAM Elements and Estimating Methodology Flow
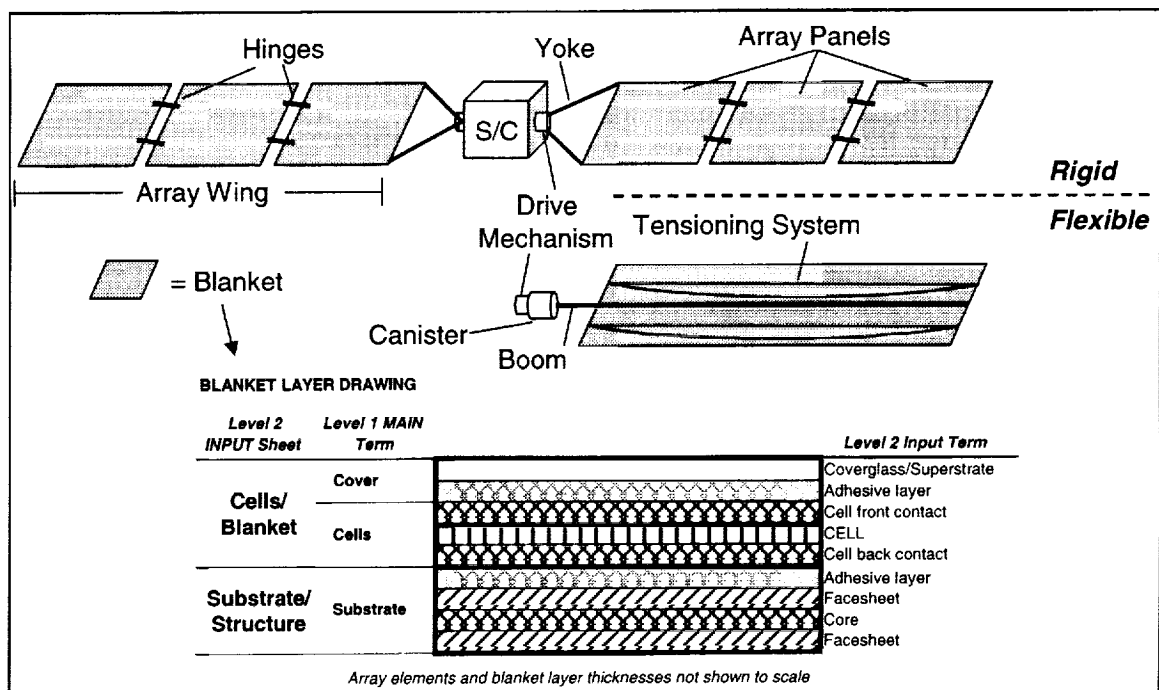
Figure 4 – Solar array hardware elements and ADAM model nomenclature.
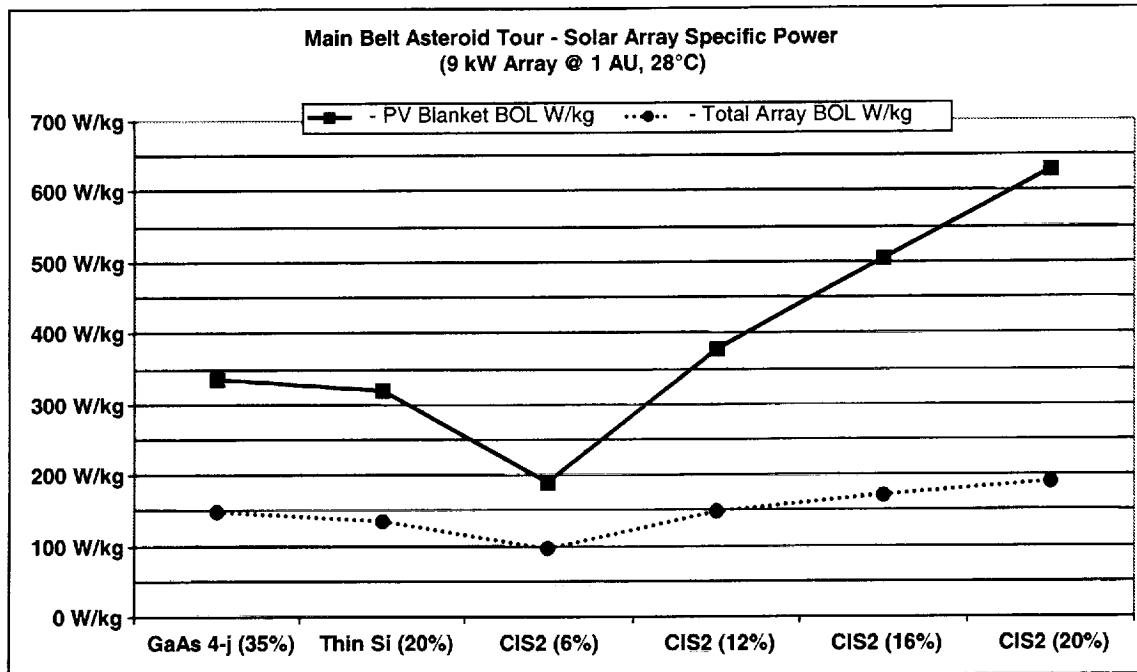
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Figure 5 - PV blanket and total solar array specific power.
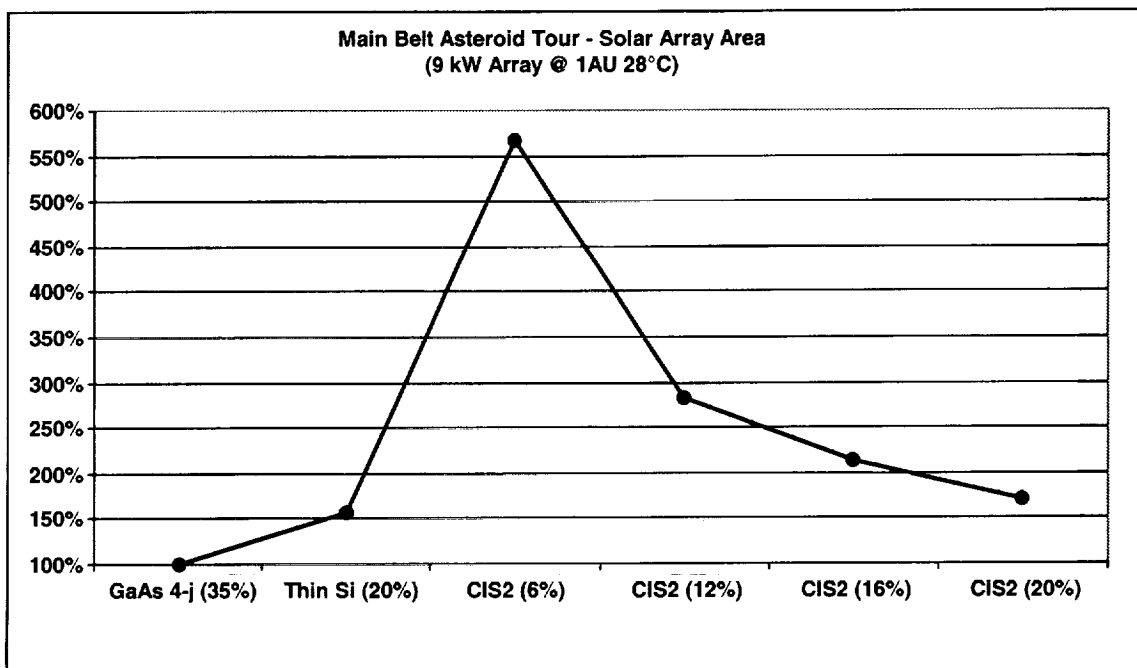
Figure 6 - Relative solar array total area (GaAs 4-j = 50 m² total).

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Main Belt Asteroid Tour Solar Array (9 kW @ 1 AU 28°C) with a Flexible Substrate
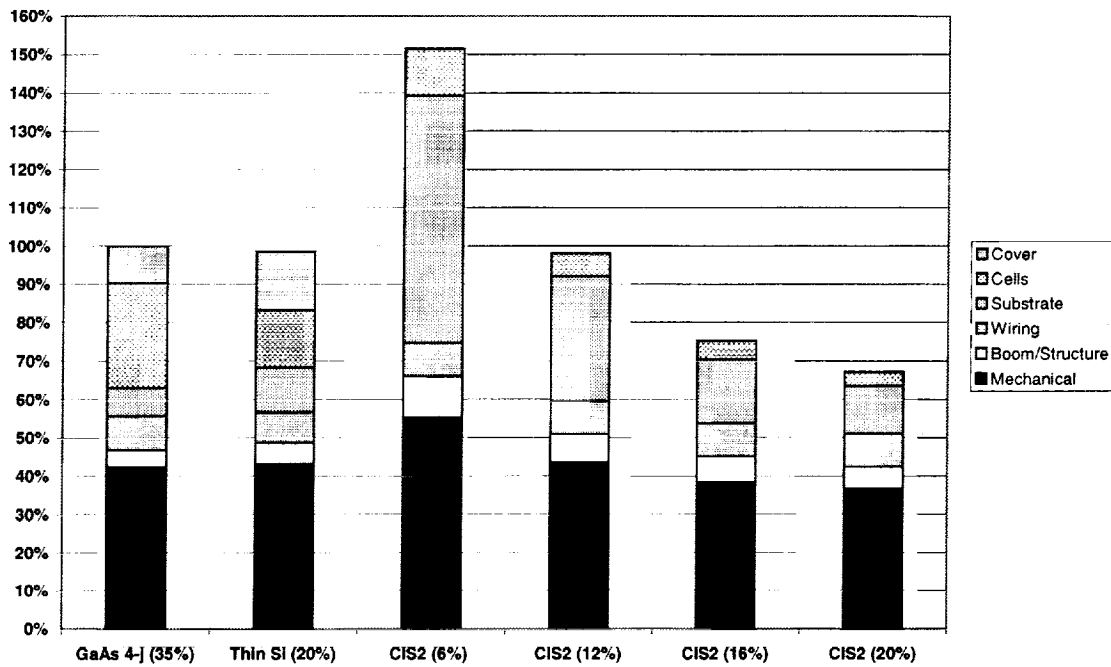*Array Mass Breakdown* with Different Cell Technology

Figure 7 - Solar array mass breakdown and relative comparison (GaAs 4-j = 121 kg).

Main Belt Asteroid Tour Solar Array (9 kW @ 1 AU 28°C) with a Flexible Substrate
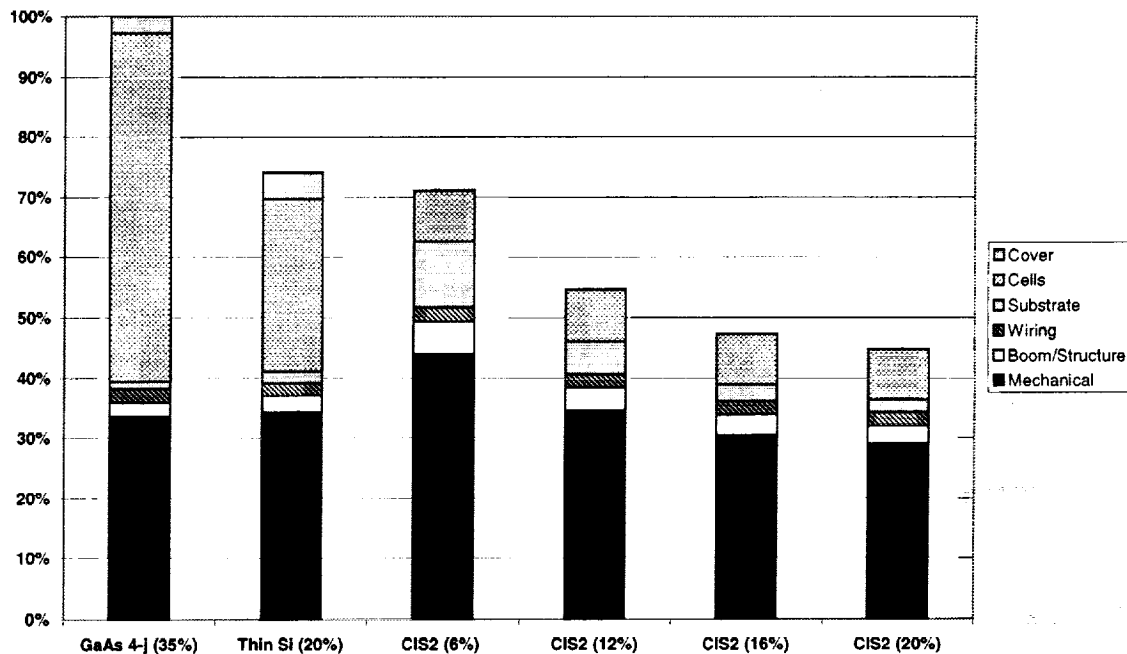*Array Cost Breakdown* with Different Cell Technology

Figure 8 - Solar array cost breakdown and relative comparison (GaAs 4-j = $14.1M).
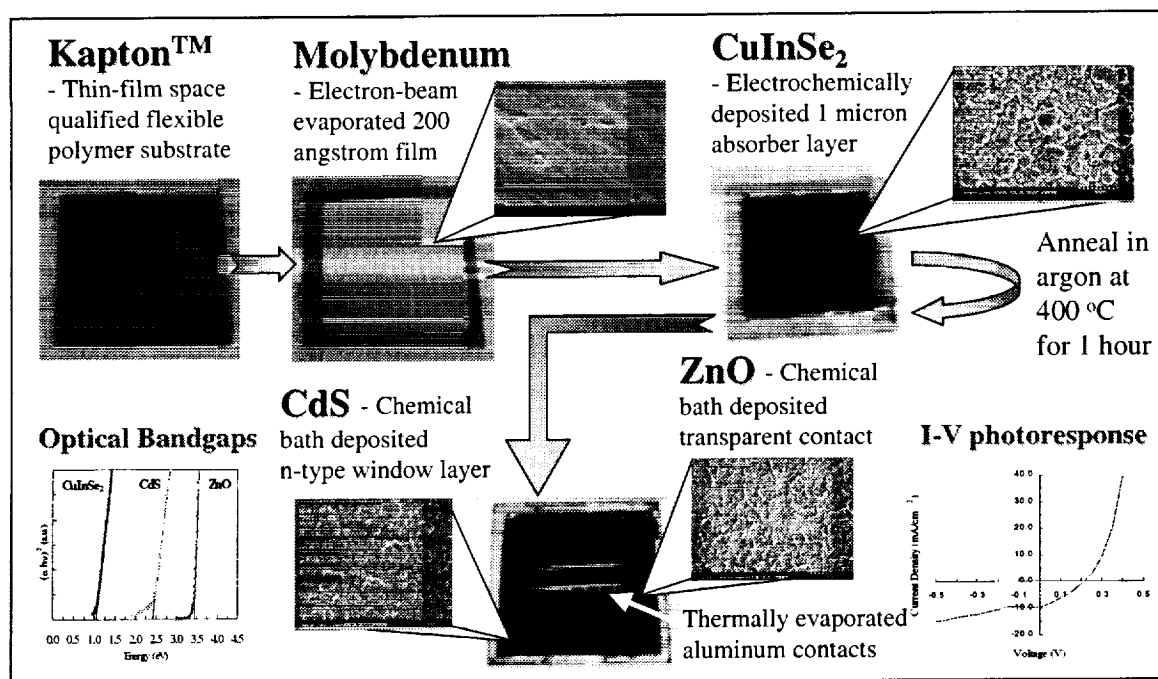
Kapton™
- Thin-film space qualified flexible polymer substrate

Molybdenum
- Electron-beam evaporated 200 angstrom film

CuInSe₂
- Electrochemically deposited 1 micron absorber layer

Anneal in argon at 400 °C for 1 hour

Optical Bandgaps

CdS - Chemical bath deposited n-type window layer

ZnO - Chemical bath deposited transparent contact

I-V photoresponse

Thermally evaporated aluminum contacts

Figure 9 - NASA GRC thin-film cell approach.

Table 1 - Summary Descriptions of ADAM Database, Inputs and Outputs.

Database Summary	Inputs Summary	Outputs Summary

6 Cell Candidates
 	
1 Rigid Substrate Type
 	
5 Flexible Substrate Types
 	
Over 50 Material Candidates
 	
8 Mission Types
  - 2 Earth Orbiting
  - 4 Planetary
  - 2 Lunar/Mars Landers
 	
8 Operating Environments (specific to Mission Types)
	4 Primary Inputs:
	  - Mission Type
	  - Operating Environment
	  - EOL Power Required
	  - Array Design Lifetime
	
	24 Level 1 Inputs:
	  - 4 Mission
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13. ABSTRACT (Maximum 200 words)

This paper summarizes a study that had the objective to develop a model and parametrically determine the circumstances for which lightweight thin-film photovoltaic solar arrays would be more beneficial, in terms of mass and cost, than arrays using high-efficiency crystalline solar cells. Previous studies considering arrays with near-term thin-film technology for Earth orbiting applications are briefly reviewed. The present study uses a parametric approach that evaluated the performance of lightweight thin-film arrays with cell efficiencies ranging from 5 to 20 percent. The model developed for this study is described in some detail. Similar mass and cost trends for each array option were found across eight missions of various power levels in locations ranging from Venus to Jupiter. The results for one specific mission, a main belt asteroid tour, indicate that only moderate thin-film cell efficiency (~12 percent) is necessary to match the mass of arrays using crystalline cells with much greater efficiency (35 percent multi-junction GaAs based and 20 percent thin-silicon). Regarding cost, a 12 percent efficient thin-film array is projected to cost about half as much as a 4-junction GaAs array. While efficiency improvements beyond 12 percent did not significantly further improve the mass and cost benefits for thin-film arrays, higher efficiency will be needed to mitigate the spacecraft-level impacts associated with large deployed array areas. A low-temperature approach to depositing thin-film cells on lightweight, flexible plastic substrates is briefly described. The paper concludes with the observation that with the characteristics assumed for this study, ultra-lightweight arrays using efficient, thin-film cells on flexible substrates may become a leading alternative for a wide variety of space missions.

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